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by

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United States
Naval Postgraduate School

THESIS

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Winfred Dan Vallance

Thesis Advisor: Edmund A. Milne

March 1971

Design and Construction of an Apparatus to Measure the Excitation Cross Sections of Molecular Nitrogen When Bombarded by Low Energy Electrons

by

Winfred Dan Vallance
Lieutenant, United States Navy
B.S., University of Texas, 1964

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

An apparatus was designed and constructed to measure the absolute cross sections for forming the $B^2\Sigma_u^+$ state of N_2^+, which gives rise to the first negative band system of N_2^+; and the $C^3\pi_u$ state of N_2, which gives rise to the second positive band system of N_2, in the lowest vibrational energy level when gaseous molecular nitrogen is bombarded by electrons in the energy range 50 eV to 2,000 eV.

The machine was constructed such that the reaction rate will be measured by counting the photons from the electromagnetic decay of these states while the gas is in a steady state condition.

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My special thanks go to Mr. Thomas Maris of the technical staff of the school for his outstanding technical assistance. Much of the final design of the apparatus can be directly attributed to Mr. Maris.

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I. INTRODUCTION

A knowledge of the excitation cross sections of atmospheric gases by electron impact is of considerable importance to the understanding of phenomena occurring in the upper atmosphere of the earth. The design and construction of an apparatus to measure some of these excitation cross sections was undertaken at the Naval Postgraduate School in support of a study of the properties of the atmospheric gases. The project was funded by the Naval Ordnance Laboratory.

The initial cross sections of interest were for the following transitions:

$$e + N_2(X^1\Sigma_g^+) \rightarrow N_2^+(B^2\Sigma_u^+) + 2e, \qquad (1)$$

and

$$e + N_2(X^1\Sigma_g^+) \rightarrow N_2(C^3\pi_u) + e. \qquad (2)$$

The first transition gives rise to the first negative band system $(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+)$ of N_2^+, and the second transition gives rise to the second positive band system $(C^3\pi_u \rightarrow B^3\pi_g)$ of N_2.

The simultaneous ionization and excitation cross section of the first transition has been measured in the energy range 70 eV to 4,000 eV by Srivastava and Mirza [1].

The goal of this work was to design and construct an apparatus to measure the cross sections for forming the $B^2\Sigma_u^+$ state of N_2^+ and the $C^3\pi_u$ state of N_2 in the lowest vibrational energy level when gaseous molecular nitrogen is bombarded by electrons in the energy range 50 eV to 2,000 eV.

II. DESIGN CONSIDERATIONS

A. GENERAL

The lowest vibrational level of the $B^2\Sigma_u^+$ state of N_2^+ decays electromagnetically to the $X^2\Sigma_g^+$ states of N_2^+ in the v'' progression (0,0), (0,1), (0,2), and (0,3)[1]; and the lowest vibrational level of the $C^3\pi_u$ state of N_2 decays electromagnetically to the $B^3\pi_g$ states of N_2 in the v'' progression (0,0), (0,1), (0,2), (0,3), and (0,4)[2]. The transition probabilities per unit time $\lambda_{v'v'}$ for these transitions are given by Nicholls [2]. In either case, the highest decay probability is for the (0,0) transition. The wavelength for the N_2^+ transition is 3914 angstroms, and the wavelength for the N_2 transition is 3371 angstroms. The apparatus was designed to count the number of (0,0) photons per second during steady state conditions.

B. DETERMINATION OF PARAMETERS

Consider a small volume of nitrogen gas being bombarded by a uniform beam of electrons as shown in Figure 1. J is the current density of the beam, A is the cross sectional area of the electron beam, L is the length of the volume δV being observed by the detector, d is the distance from the volume to the detector, and Ω is the solid angle of the detector. Assume d >> L.

After bombarding the gas for a time t, t >> τ, where τ is the mean life of the excited state, a steady state condition will exist.

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[1]The vibrational energy of the upper state, given by the quantum number v', and the vibrational energy level of the lower state, given by the quantum number v'', are denoted by (v',v'').

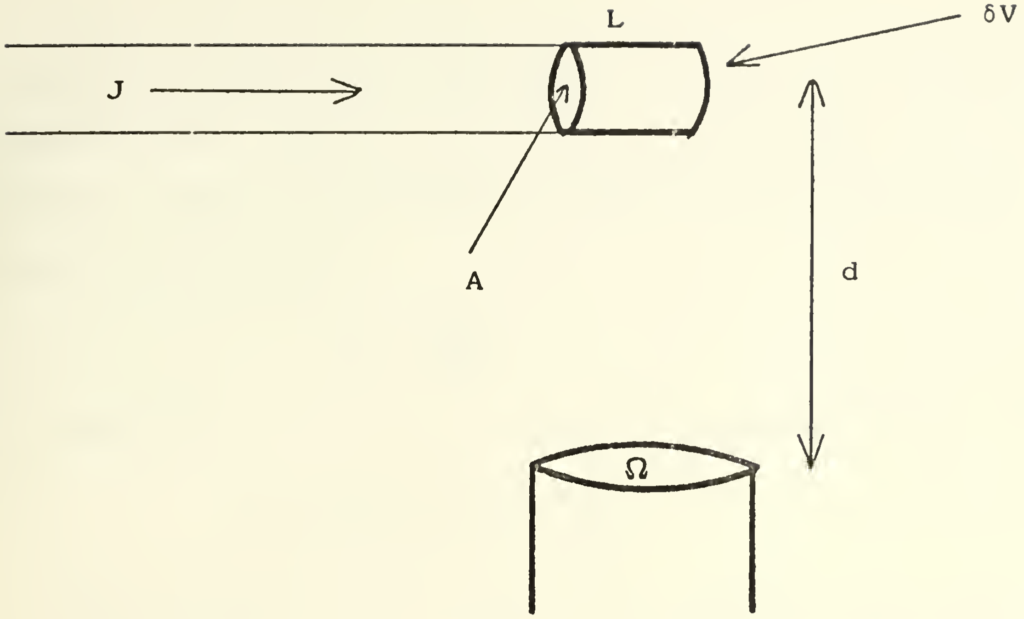


FIGURE 1

Under the steady state condition, the excitation rate and the de-excitation rate of an excited state k are equal, and

$$\frac{dN_k}{dt} = R_k - \sum_{i=o}^{f} \lambda_{oi} N_k - Q = 0. \tag{3}$$

Where N_k is the population of the excited state k in the volume δV, R_k is the rate of formation of the excited state k, $\Sigma \lambda_{oi} N_k$ is the electromagnetic decay rate, and Q is the collisional decay rate. If the pressure of the gas is sufficiently low, $Q \ll \Sigma \lambda_{oi} N_k$, and

$$R_k \approx \Sigma \lambda_{oi} N_k = \lambda_{oo} N_k \Sigma \frac{\lambda_{oi}}{\lambda_{oo}} . \tag{4}$$

The cross section σ for forming the excited state k is defined by

$$R_k = \frac{N\sigma J}{e} . \tag{5}$$

Where N is the number of molecules in δV, and e is the charge of one electron. Since $J = I/A$, and $N = n\delta V$, where I is the beam current, and n is the number of molecules per unit volume, equation (5) becomes

$$R_k \approx \frac{n\sigma I L}{e} \quad . \tag{6}$$

Equating equations (4) and (6) and solving for σ, yields

$$\sigma = \frac{e}{I n L} \lambda_{oo} N_k \sum_{i=o}^{f} \frac{\lambda_{oi}}{\lambda_{oo}} \quad . \tag{7}$$

$\lambda_{oo}N_k$ is the rate of (0,0) transitions, and the count rate C observed by the detector is given by

$$C = \epsilon \frac{\Omega}{4\pi} \lambda_{oo} N_k . \tag{8}$$

Where ϵ is the efficiency of the counting equipment.

For an ideal gas,

$$n = \frac{P}{kT} \quad . \tag{9}$$

Where P is the absolute pressure of the gas, k is the Boltzmann constant, and T is the absolute temperature of the gas.

Solving equation (8) for $\lambda_{oo}N_k$ and substituting equations (8) and (9) into equation (7) leads to

$$\sigma = \frac{4\pi k e}{\Omega \epsilon L} \sum_{i=o}^{f} \frac{\lambda_{oi}}{\lambda_{oo}} \frac{TC}{IP} \quad . \tag{10}$$

Equation (10) is the expression that will be used to determine σ. The four parameters that must be determined during the experiment are the temperature, the count rate, the current, and the

pressure. Assuming that the interaction chamber is in thermal equilibrium with the atmosphere, the temperature can be taken as the room temperature.

C. PRESSURE CONSIDERATIONS

The gas pressure must be low enough so that the collisional de-excitation rate of the excited state can be neglected when compared to the electromagnetic decay rate. Consider the gas to be spheres of diameter d that can interact with each other only by collisions. The mean free path ℓ between collisions is [3]

$$\ell = \frac{1}{\sqrt{2}\,\pi n d^2} \quad . \tag{11}$$

Where n is the number of molecules per unit volume.

For an ideal gas,

$$U = 3/2\ kT = 1/2\ mv^2 , \tag{12}$$

and

$$n = \frac{P}{kT} \quad . \tag{9}$$

Where U is the average energy per molecule, k is the Boltzmann constant, T is the absolute temperature, m is the mass of the molecule, v is the root-mean-square velocity of the molecule, and P is the absolute pressure.

Combining equations (11), (12), and (9), the average time between collisions t_C is

$$t_C = \frac{\ell}{v} = \frac{\sqrt{mkT}}{\sqrt{6}\pi d^2 P} \quad ; \tag{13}$$

and, solving for P,

$$P = \frac{\sqrt{mkT}}{\sqrt{6}\pi d^2 t_C} . \tag{14}$$

The mean life τ of these two excited states of nitrogen are on the order of 10^{-8} seconds [4]. The collisional decay rate is small compared to the electromagnetic decay rate, if

$$t_C > 10^{+3}\tau \approx 10^{-5} \text{ sec.} \tag{15}$$

Using $m = 4.65 \times 10^{-26}$ kgms, $d = 2 \times 10^{-10}$ meters, $T = 300$ K, and $t_C > 10^{-5}$ seconds in equation (14) and solving for P, gives

$$P < 3.4 \times 10^{-3} \text{ torr.} \tag{16}$$

This experiment was designed to operate at a gas pressure of $1\text{-}3 \times 10^{-4}$ torr. The assumption that the collisional decay rate can be neglected can be tested during the experiment to see if the count rate is proportional to the current and pressure as given in equation (10).

III. EXPERIMENTAL APPARATUS

Figure 1 is a schematic view of the apparatus that was constructed for the experiment. The major components of the system are (1) the outer chamber, (2) the vacuum pumping system, (3) the electron beam, (4) the interaction chamber, (5) the optics, and (6) the counting equipment. Each of these and the method of operation are described below.

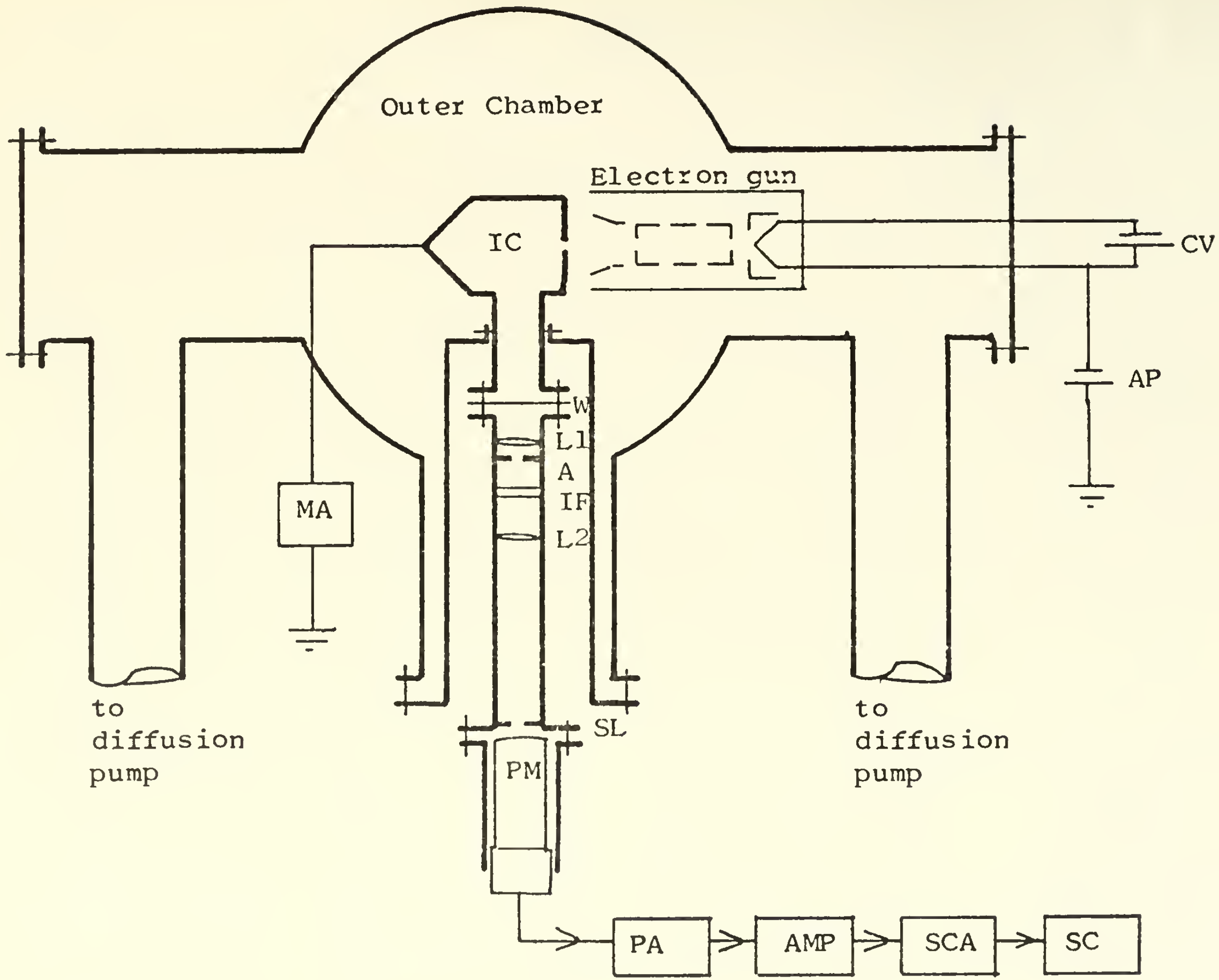
A. OUTER CHAMBER

The outer chamber is a right, circular cylinder with an eighteen inch diameter and a ten inch length. The outer chamber houses the interaction chamber and the electron gun as shown in Figure 2. Electrical connections for the electron gun and interaction chamber are made in the walls of the outer chamber using glass feed-throughs. A gas inlet line and a pressure line pass through the outer chamber to the interaction chamber.

The vacuum in the outer chamber is measured by an ion gauge and is maintained by the vacuum pumping system which is attached to the outer chamber by two six-inch lines, one on each end of the outer chamber.

B. INTERACTION CHAMBER

The interaction chamber is a two inch diameter copper pipe with a one and one-half inch "T" outlet for the optics as shown in Figure 2. The pipe is three and five-eighths inches long. The



SYMBOLS

A   Aperture
AMP Amplifier
AP Accelerating potential
CV Cathode voltage
IC Interaction chamber
IF Interference filter
L1 Lens 1
L2 Lens 2
MA Microammeter
PA Preamplifier
PM Photomultiplier tube
SC Scalar
SL Slit
SCA Single channel analyzer
W   Quartz window

FIGURE 2

tapered back of the interaction chamber is two inches long and is made of aluminum. It has a one-eighth inch plugged hole in the center to facilitate optical alignment of the interaction chamber with the beam.

The seven-sixteenth inch thick aluminum faceplate is insulated from the remainder of the interaction chamber. The faceplate has a one-eighth inch diameter hole in the center that admits a well defined electron beam into the interaction chamber. The faceplate is grounded to carry off that part of the electron beam that strikes the faceplate.

The inside of the interaction chamber is coated with acquadag to prevent light reflections from its walls. The interaction chamber is shielded so that outside light can enter only through the hole that admits the electron beam. During operation, any light that enters the hole will be absorbed by the walls before it can be reflected into the optics.

The entire interaction chamber, except for the faceplate, is a faraday cup and is connected through an microammeter to ground. Assuming that a negligible number of electrons inside the interaction chamber is absorbed by the faceplate, the current indicated by the microammeter will be the beam current.

Gas is fed through a variable leak into the interaction chamber. A differential pressure is maintained between the interaction chamber and the outer chamber by the hole in the faceplate. The differential pressure can be adjusted by varying the rate that gas is bled into the interaction chamber.

Pressure is measured in the interaction chamber with a Baratron Type 170 series manometer which can measure a differential pressure from 10^{-5} torr to one torr. The high pressure side is connected to the interaction chamber, and the low pressure side is connected to a reference vacuum at about 10^{-7} torr. If the pressure in the interaction chamber is of the order of 10^{-4} torr, the differential pressure read on the Baratron is essentially absolute pressure.

When not taking data, pressure in the interaction chamber can be measured by a thermocouple and an ion gauge. The ion gauge is shielded with analuminum box to prevent entry of unwanted light.

C. VACUUM PUMPING SYSTEM

The vacuum pumping system has two six-inch oil diffusion pumps rated at 1800 liters per second each connected in parallel. A refrigerated baffle is used between each diffusion pump and the outer chamber to prevent pump oil from entering the system. The system connects to the outer chamber as shown in Figure 2. The two diffusion pumps discharge to a 15 cfm, two-stage mechanical pump.

D. ELECTRON BEAM

The electron beam originates from the electron gun which was taken from a RCA 7JP-4 television tube. The indirectly heated cathode was replaced by a directly heated, "V" shaped cathode made

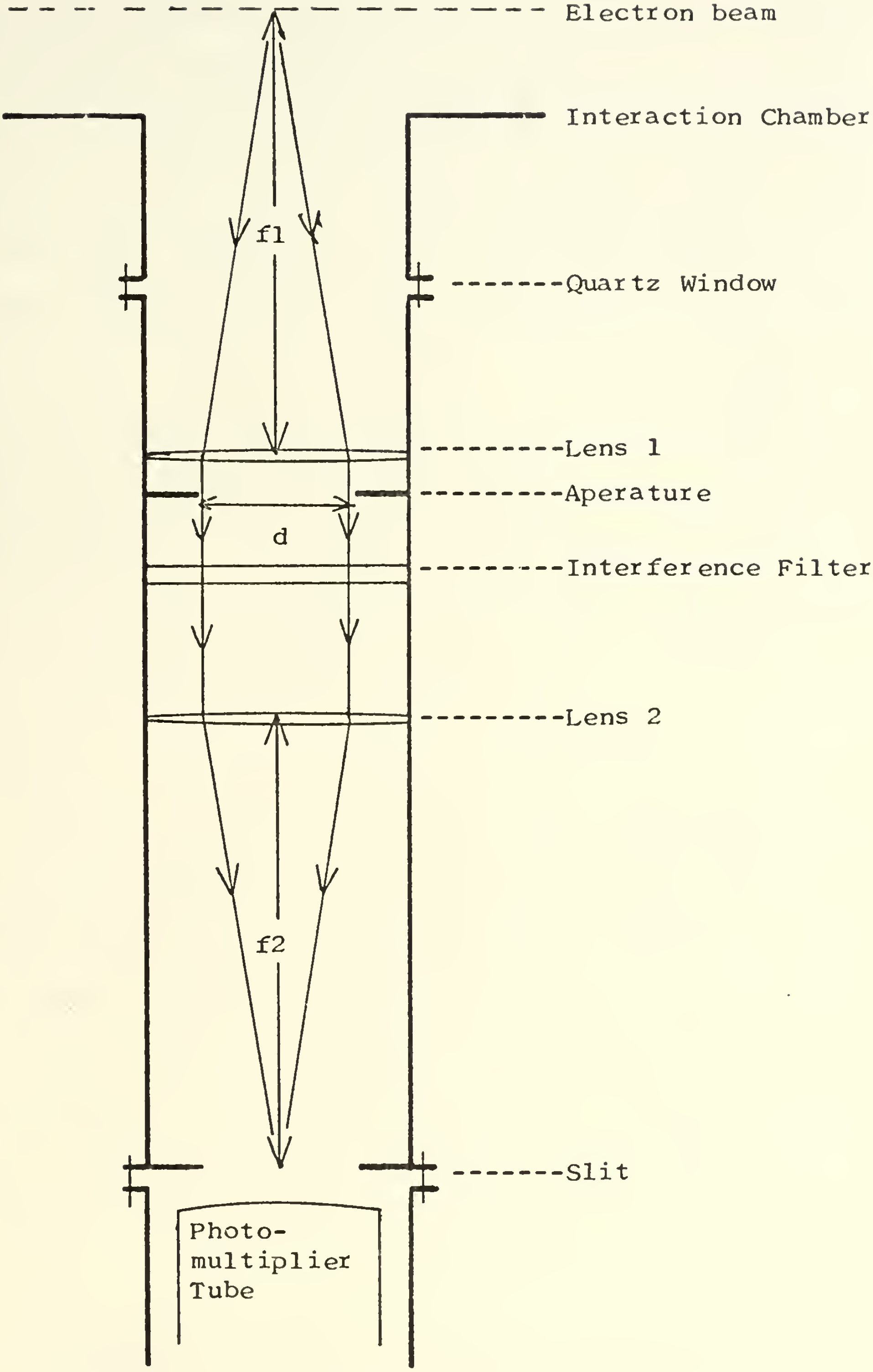

Electron beam
Interaction Chamber
f1
Quartz Window
Lens 1
Aperature
d
Interference Filter
Lens 2
f2
Slit
Photo-
multiplier
Tube

FIGURE 3

of .010 inch diameter tungsten wire. The electron extractor, the focusing system, and the deflection system were left intact. By removing the cathode, the electron gun can be aligned with the two holes in the interaction chamber using an optical laser.

The accelerating potential is connected between the cathode and ground as shown in Figure 2. Electrons leave the cathode and are accelerated toward the grounded interaction chamber. Most of the beam is caught by the faceplate, but a well defined one-eighth inch diameter beam enters the interaction chamber through the hole in the faceplate. The electric field inside the interaction chamber is zero, the the electrons have an energy equal to the accelerating potential in electron volts.

E. OPTICS

The optics is shown in Figure 2 and in more detail in Figure 3. The optical arrangement is very similar to that used by Srivastava and Mirza [1]. The optics was designed to detect the radiation at right angles to the beam direction through a quartz window and a narrow band interference filter. The electron beam is at the focal point of lens 1, and the slit at the mouth of the photomultiplier tube is at the focal point of lens 2. Light that passes through the optical system is parallel to the optical tube between lens 1 and lens 2.

The length of the beam observed by the photomultiplier tube is equal to the length of the slit (seven-eighths inch) at the mouth

of the photomultiplier tube. The solid angle viewed by the optics is determined by the diameter d (seven-eighths inch) of the aperture behind lens 1 and the distance fl (five inches) from lens 1 to the beam. The solid angle is given by

$$\Omega = \frac{\pi\left(\frac{d}{2}\right)^2}{\pi(fl)^2} 4\pi = .096 \text{ steradians.} \tag{17}$$

The angle of incidence[2] of the light into the interference filter can be adjusted by changing the angle that the filter is placed in the light beam. As the angle of incidence is shifted from zero degrees, the peak wavelength passed by the filter is shifted to shorter wavelengths. Interference filters with peak wavelengths of 3950 angstroms and 3400 angstroms will be used for the 3914 angstroms and 3371 angstroms lines respectively. Both filters have a bandwidth of 60 angstroms.

The optical system is made so that the optical tube can be disconnected between the quartz window and lens 1. A quartz window similar to the installed window can be used with the disconnected optics so that the efficiency of the optical system and the counting equipment can be obtained using the calibration procedures given in Refs. 5 and 6. An EG&G Model 590 calibrated lamp system will be used as a black body.

F. THE COUNTING EQUIPMENT

The radiation is detected by a RCA 7265 photomultiplier tube which is cooled by a liquid nitrogen cooler. Cold, gaseous

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[2]The angle of incidence is measured from the normal to the filter.

nitrogen is introduced between the photomultiplier tube window and lens 2 to prevent the window from frosting.

The signal goes from the photomultiplier tube through a preamplifier (Canberra Model 808), an amplifier (Canberra Model 810), and a single channel analyzer (Canberra Model 830) to a scalar (Hewlett Packard Model 5202L).

IV. PROGRESS

A. ASSEMBLY

The apparatus has been assembled as shown in Figure 2, the electron beam has been aligned with the interaction chamber, and the optical system has been focused. The optics is set up for the 3914 angstroms line.

B. TESTS NOT COMPLETED

The counting equipment and optical system have not been tested with the apparatus actually operating, and they have not been calibrated using the black body source. However, the counting equipment will count the photons in a small white light source. The liquid nitrogen cooler reduces the dark current count from the photomultiplier tube to about four per second. A similar optical system was successfully used by Srivastava and Mirza [1,5], and no unsolvable problems are anticipated.

The Baratron Pressure measuring system has not been tested.

C. TESTS COMPLETED

1. Vacuum Pumping System

The vacuum pumping system has been completely tested. The system will maintain the vacuum inside the outer chamber, in the neighborhood of the interaction chamber and electron gun, around 10^{-6} torr while the vacuum inside the interaction chamber is varied through the 10^{-4} torr range.

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2. Electron Beam

The electron beam has been tested for electron energies from 50 eV to 1,000 eV. The electron gun will emit more than 10^{-4} amperes at a temperature of 2400 degrees celsius. The beam can be focused so that more than 10^{-8} amperes can be obtained inside the interaction chamber in the above energy range (preliminary calculations show that 10^{-9} amperes is sufficient).

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13. ABSTRACT

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Nitrogen						
Simultaneous ionization and excitation cross section						
First negative band system N_2^+						
Second positive band system of N_2						
Molecular Nitrogen						

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